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Summary: The wave induced hydrodynamics of rigid and flexible foils are investigated by means of experimentation, including Particle Image Velocimetry (PIV), and analytically through Theodorsen's unsteady loading theory. High-amplitude high-frequency fluctuations were investigated in order to explore extreme flow fluctuations, which cannot be matched by a pitch control system, and to assess the limits of Theodorsen's linear approach. We found a strong non-linear interaction between the separated boundary layer and the trailing edge vortex, with circulation counter to the bounded case present. This resulted in low lift-to-drag ratio (i.e. low efficiency) and poor agreement between Theodorsen and experiments for the rigid foil. Conversely, the flexible foil was very promising: preventing large flow separation, it resulted in 25% higher lift-to-drag ratio, 30% lower flow fluctuations and reasonable agreement with Theodorsen's prediction.

Introduction

A submerged foil experiences wave-induced flow fluctuations resulting in periodic load variations. In the case of tidal turbine blades, peak load fluctuations can lead to dynamic failures while multiple load cycles can lead to fatigue failures. Therefore, it is critical that the nature of dynamic loading is fully understood; that accurate predictive tools are developed and that mitigating technologies are conceived. Unsteady loading on tidal turbines has been investigated measuring the thrust and torque at model-scale [1-3], and predictive tools based on the Morrison equation [1], Vortex Lattice Method [2], and Loewy's theory and Theodorsen's [4] have been developed. The latter theory is used in the state-of-the-art industry standard design tool Tidal Bladed Research. However, significant disagreement between numerical and experimental results have been reported [3]. While differences were thought to be due to flow separation and dynamic stall (which Theodorsen does not account for), flow measurements around the blades have never been performed to investigate these phenomena. In this paper we compare the loads measured experimentally on model-scale blades with those predicted by Theodorsen's theory. We then discuss the differences through the analysis of the flow field measured with PIV. The focus is on large-amplitude fluctuations in order to explore non-linear effects; and on high-frequencies (six per turbine revolution) which cannot be matched by a pitch control system. Most wind turbine flow-control techniques used to mitigate load fluctuations cannot be adopted by the tidal industry because they are incompatible with the harsh marine environment. For example, marine biofouling precludes the use of moving appendages and recessions. An emerging means for flow control, which could be employed by tidal turbines, is the use of flexible materials. Here we investigate blades with a flexible trailing edge.

Method

We 3D-printed a rigid and a flexible NACA 4415 foil, with a chord of 0.15 m extruded spanwise for 0.3 m. The Young's modulus of the flexible material was 0.97 MPa. We mounted the models between two splitter plates and immersed them at mid-depth in the University of Edinburgh's combined wave-current flume, which is 0.4 m wide and has a water depth of 0.45 m. We tested at a Reynolds number of 7.5×10^4. We generated opposing waves with Froude number 0.53, reduced frequency 1.9, steepness 0.04, depth/chord ratio 1.5 and relative depth 1.25 (see ref. [5] for further details). Lift and drag forces were measured with two independent load cells, PIV measurements were performed on the mid-span section at 7.5 Hz, and turbulence statics were measured via Laser Doppler Velocimetry at mid-depth, ten chords upstream of the model.

Results

The wave orbitals led to large-amplitude periodic variations of the flow speed ($U_{\mathrm{rel}} \in [0.76,1.22]\times U_{ref}$, where U_{ref} is the current velocity without waves) and of the angle of attack ($\alpha_{\mathrm{tot}} = 10° + \alpha$, where $\alpha \in [-13°, 13°]$). A phase delay of $\pi/2$ occurs between U_{rel} and α. The turbulence intensity was 3%. Figure 1 shows the anti-clockwise hysteresis loop of the lift force variation (divided by the dynamic pressure based on U_{rel}) versus α. When $\alpha = 0$ and is increasing (point A in fig. 1), U_{rel} is maximum and trailing edge separation occurs on both foils. This separation is associated with anti-clockwise circulation (a trailing edge vortex), which decreases the bound circulation around the foil and thus leads to a loss of lift (Δ Lift < 0). For the rigid model, in steady conditions, any further increase of α would lead to stall. However here α increases by 13° ($\alpha_{\mathrm{tot}} = 23°$)

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and only a mild boundary layer separation was observed on both foils. The deflection of the flexible trailing edge leads to a change in the orientation of the chord, defined as a line joining the leading and trailing edge of the foil. This results in a lower α oscillation ($\alpha \in [-4°, 4°]$) as compared to the rigid foil. The loss of momentum associated with the boundary layer separation is significantly reduced for the flexible model. When $\alpha = 0$ and is decreasing (point B in fig. 1), U_{rel} is minimum and boundary layer separation is clearly visible on the upper side of both foils. The α decrease prevents stall and the flow with low momentum slowly convects downstream along the foils. When the cycle restarts and α begins to increase again, the low momentum flow has reached the trailing edge and therefore strengthens the counter-rotating trailing edge vortex that begins to form. On the flexible foil, where less momentum is lost in the boundary layer, a much smaller trailing edge vortex is formed than on the rigid foil. This was further reflected in a 25% increased lift-to-drag ratio for the flexible model over the rigid model. The strong non-linear interaction between the separated boundary layer and the trailing edge vortex leads to a poor prediction using Theodorsen's theory for the rigid model. It should be noted that the effect of the shed circulation is opposite to that of the added mass (AM in fig. 1), which shows a clockwise hysteresis loop.

Conclusions

We found that wave-induced, large-amplitude, high-frequency flow fluctuations lead to periodic trailing edge separation (not dynamic stall). On a rigid model, this results in dynamic loads more than 20% higher than for current alone. Theodorsen's method, which is used in industry, may predict load fluctuations more than double that which was observed here. This highlights the need for advanced predictive tools. A flexible trailing edge can be used to mitigate load fluctuations by more than 30% and to increase efficiency by more than 25%, preventing large flow separation.

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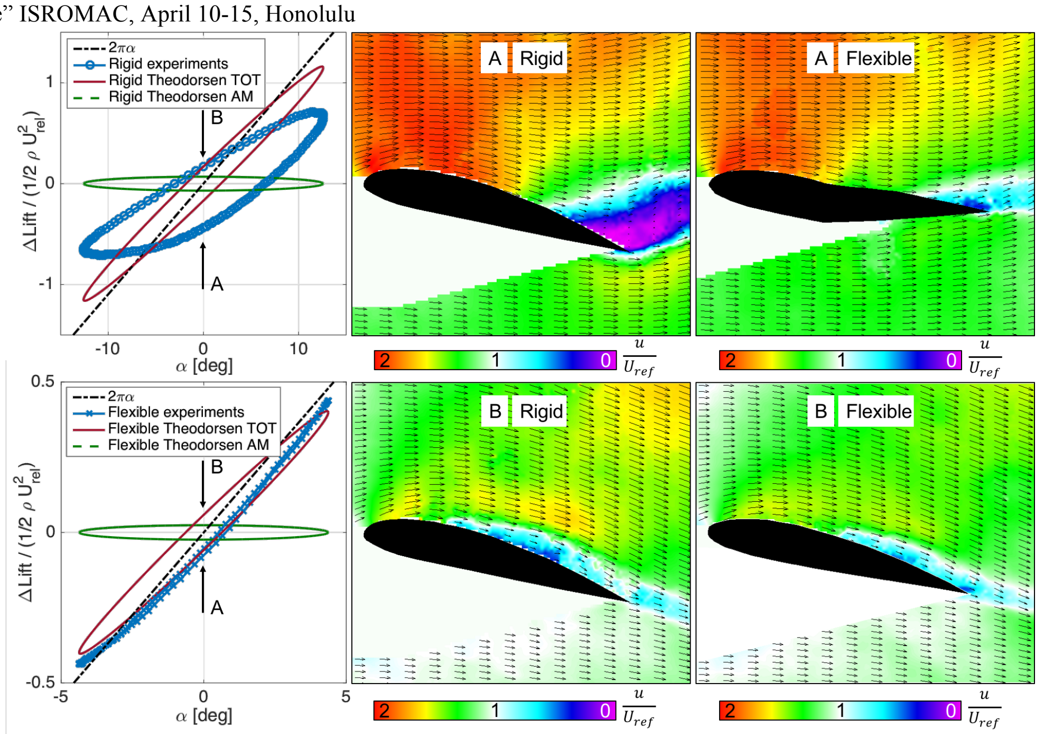

Fig. 1: Lift variations and flow fields for a rigid and a flexible model subjected to wave-induced large-amplitude high-frequency flow fluctuations.